On the Mass-Period Correlation of the Extrasolar Planets

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ABSTRACT

We report on a possible correlation between the masses and periods of the extrasolar planets, manifested as a paucity of massive planets with short orbital periods. Monte-Carlo simulations show the effect is significant, and is not solely due to an observational selection effect. We also show the effect is stronger than the one already implied by published models that assumed independent power-law distributions for the masses and periods of the extrasolar planets. Planets found in binary stellar systems may have an opposite correlation. The difference is highly significant despite the small number of planets in binary systems. We discuss the paucity of short-period massive planets in terms of some theories for the close-in giant planets. Almost all models can account for the deficit of massive planets with short periods, in particular the model that assumes migration driven by a planet-disk interaction, if the planet masses do not scale with their disk masses.

Subject headings: binaries: general — planetary systems — stars: individual (τ Boo, HD 195019, Gl 86) — stars: statistics

1. INTRODUCTION

The mass distribution of the extrasolar planets was recognized to be a key feature of the growing new population since the first few detections (e.g., Basri & Marcy 1997; Mayor, Queloz & Udry 1998; Mazeh, Goldberg & Latham 1998; Heacox 1999; Mazeh 1999; Stepinski & Black 2000). Recent studies showed that the mass distribution is probably flat or slightly decreasing in log M (Jorissen, Mayor & Udry 2001; Zucker & Mazeh 2001; Tabachnik & Tremaine 2002; Lineweaver & Grether 2002), and has a distinct cutoff at about 10 Jupiter masses($=M_J$). This paper focuses on a possible dependence between the extrasolar planets masses and their orbital periods.

Every study of the mass-period relation has to take into account the strong observational selection effect that prohibits the detection of low-mass–long-period planets, because of their small radial-velocity amplitudes. Tabachnik & Tremaine (2002) studied the mass and the period distributions simultaneously, assuming they were two independent power-law distributions. They found that the uncertainties of the exponents of the two variables are highly correlated, but attributed their findings to the observational selection effect. This paper shows that the mass-period correlation found in the sample of known extrasolar planets *cannot* be attributed solely to the observational selection effect. We show that there is an additional real dependency between the mass and the period of the extrasolar planets, manifested as a significant paucity of high-mass–short-period planets. Since such planets are the easiest to detect, this paucity is probably not the result of any selection effect.

In Section 2 we present our analysis of the mass-period correlation of the whole sample of known planets. Section 3 shows that the small subsample of planets in binary stellar systems may have different, opposite, correlation. Section 4 shortly discusses our findings in terms of some theories for the existence of giant planets close to their host stars, the migration model in particular. A preliminary version of this work was presented in Mazeh & Zucker (2002).

2. Analysis

Figure 1 presents the minimum masses of all known extrasolar planets as a function of their orbital periods. The data were taken from the web-site of the California Planet Search Team[1], and were updated as of December 2001. We chose to plot the two axes with logarithmic scales, because the frequency of planets, up to 10 M_J, is almost flat in log M (Jorissen, Mayor & Udry 2001; Zucker & Mazeh 2001; Tabachnik & Tremaine 2002), as well as in log P (Heacox 1999; Stepinski & Black 2001; Mazeh & Zucker 2002; but see a somewhat different approach by Tabachnik & Tremaine 2002).

We concentrated in this analysis on a trapezoidal area in the minimum-mass–period parameter space bounded by dashed lines in the figure. The upper boundary corresponds to the 10 M_J cutoff in planets masses (e.g., Jorissen, Mayor & Udry 2001; Zucker & Mazeh 2001). Although Zucker & Mazeh (2001) suggested a probable small higher-mass tail beyond the 10 M_J line, the distribution is flat up to, probably, 10 M_J. We plot the five objects above the line for completeness. The two vertical lines represent the minimum and maximum orbital periods found in the sample.

The ascending line at the bottom of the figure corresponds to a constant radial-velocity

[1]http://exoplanets.org/planet_table.txt

amplitude, K, of $25\,\mathrm{m\ s^{-1}}$. The detection rate of the present planet-search projects below this line is low. This is easily seen in the figure, which includes only five planets below this border line. Again, we plotted these five planets only for the sake of completeness. We assume that planets detected above that line have all been reported. We now proceed to analyze the 66 planets inside the trapezoid, assuming a constant detection rate over its area.

A close examination of Figure 1 reveals a paucity of planets at the high-mass–short-period corner of the trapezoid. Only three planets appear at that corner. This is certainly not a selection effect, because planets at that part of the diagram have the largest radial-velocity amplitudes, and therefore are the easiest to detect.

It is not clear yet what is the shape of the area in which we find low frequency of planets. It might have, for example, a rectangular shape bordered by $\log P = 1.6$ and $\log(M_2 \sin i) = 0.3$, or could have a wedge shape, bordered by the line from $(\log P, \log(M_2 \sin i)) = (0.46, 0.2)$ to $(1.5, 1)$. In any case, it seems that there are enough planets in the trapezoid to render this paucity significant.

To estimate quantitatively the statistical significance of the high-mass–short-period paucity seen in the figure we first consider the mass-period correlation coefficient of the sample of planets in the trapezoid. The resulting value was 0.661. We claim that this high value means there is a real correlation in the planets population — higher than the one induced by the selection effect. In terms of statistical hypotheses testing, we have to reject the null hypothesis that there is no mass-period correlation in the planets population, and the correlation we find in the sample comes solely from the wedge-shape of the area removed by the selection effect.

To assess the statistical significance of the null hypothesis rejection we used Monte-Carlo simulations in which we created an artificial sample, randomly drawn out of a two-dimensional uniform distribution in log-mass and log-period, between the period limits of the trapezoid, and between 0.175 and 10 M_J. To simulate the selection effect we have discarded every planet whose implied radial velocity was too small and drawn another one instead, until we had in hand 66 planets. The process was repeated 10^6 times, calculating the correlation for each simulated sample. Figure 2 shows the histogram of the simulated correlation coefficients together with the value derived for the original sample. The simulated correlation values distributed around a mean value of 0.336 with a standard deviation of 0.104. Only 208 simulations yielded a value larger than 0.661. Thus, we can conclude that the null hypothesis of two uniform uncorrelated random distributions of log-mass and log-period can be rejected with a 99.98% confidence level. Of course, in the currently small sample of planets, even a single additional detection of a planet with extremely short period and large mass can alter the results significantly.

The seminal work of Tabachnik & Tremaine (2002) has used maximum likelihood calculation to study the mass and period distributions of the extrasolar planets. Assuming the two distributions have power-law shape and are mutually independent, they derived a positive power of 0.26 ± 0.06 for the period distribution and a negative one, -0.12 ± 0.10, for the mass distribution. Such a distribution creates a deficiency of high-mass–short-period planets that might have produced the effect we report here. In order to check whether this is the case, we repeated the simulation process with Tabachnik and Tremaine's distribution. Indeed, the correlation values were somewhat higher than in the flat distribution case, with an average value of 0.403 and standard deviation 0.109. However, here again only 3823 simulations out of 10^6 yielded a value larger than 0.661. We can, therefore, reject this hypothesis with a 99.62% confidence level. We also checked the extremely unlikely case where the true values of both exponents are 2-σ away from the ones derived by Tabachnik & Tremaine (2002). Two independent distributions, with 0.38 for the exponent of the period distribution and -0.32 for that of the mass distribution, are still rejected at a 98% confidence level. The somewhat lower significance of the last rejection indicates that we can not reject all possible hypotheses where the mass and the period are uncorrelated, and one might come up with a specific distribution that will reproduce the reported effect, without a real correlation between the two variables.

3. Planets in Binary Stars

Having established the significance of the paucity of the short-period massive planets, we can examine Figure 1 and try to see what distinguishes the few planets in the high-mass–short-period corner. The three planets that appear to be somewhat isolated in that corner of the figure are τ Boo b, HD 195019 b and Gl 86 b — all of them are planets found in wide stellar binaries (Hale 1994; Fischer et al. 1999; Els et al. 2001). This raises the possibility that planets in binary stellar systems have a different mass-period distribution. If this is true, it can tell us about the possible effect the binarity of the parent star might have on the formation (Boss 1998; Nelson 2000) and orbital evolution of their planets (e.g., Mazeh, Krymolowski & Rosenfeld 1997; Holman, Touma & Tremaine 1997; Innanen et al. 1997; Holman & Wiegert 1999).

In order to check this hypothesis we assembled a subsample of all the planet-hosting stars that we can safely tag as binaries. Using the WDS catalog, we decided, somewhat arbitrarily, to consider only those binaries whose projected separation is smaller than 1000 AU, assuming wider binaries would not have influenced the formation and evolution of their planets. We also discarded binaries that have angular separations larger than $10''$, whose secondaries were observed to be fainter than 12th magnitude, and had no other evidence for a physical association (mainly common proper motion). We added to the final list Gl 86 which was announced after the most recent publication of the WDS. We were left with nine binary stars: HD 142, Gl 86, HD 19994, ϵ Eri, τ Boo, HD 178911 B, 16 Cyg, HD 195019, HD 217107. Figure 3 shows the two separate subsamples of planets. ϵ Eri lies outside our nominal trapezoid and thus only eight planets constitute our binary subsample.

The difference between the two subsamples in Figure 3 is striking. Apart from the enhanced paucity of planets in the upper left corner of the figure in the single-star population, the binary population shows an opposite trend. A *negative*-slope straight line, with a slope of -0.15, can be fitted to this small subsample. This is opposed to the slope of the single-star planets, for which we fit a straight line with a slope of $+0.33$. As we showed in the previous section, only part of this positive slope is due to the specific shape of the trapezoid considered, and the population of planets does show a positive slope because of the short-period–high-mass paucity. The remarked difference is also reflected by the negative mass-period correlation of -0.459 for the binary planets.

The difference between the two populations is manifested also in the *higher* value of the correlation coefficient of the subsample of 58 single-star planets — 0.783. In order to test the significance of the difference between the sample with and without the binary planets, we ran Monte-Carlo simulations again. Each iteration consisted of removing a random set of 8 planets from the original sample of 66 and re-calculating the correlation. The results of 10^6 iterations are depicted in Figure 4. The simulated values average at 0.661, the original value of the parent sample, and have a standard deviation of 0.028. Only 17 out of 10^6 simulations yielded a value higher than 0.783, thus implying a significance of 99.998% to the higher correlation of the single-star planets.

4. Discussion

We have presented evidence for a substantial deficit of massive planets with short orbital periods. We have shown that the correlation seen in the sample of known planets is higher than the one predicted by published independent power-law models and the selection effect, although we need more points to corroborate our finding. We regard this deficit as a refinement of the initial surprising discoveries of giant planets in close orbits (e.g., Mayor & Queloz 1995). We have shown that only planets with masses below about 2 M_J can frequently be found orbiting single stars with periods shorter than about 40 days. This may serve to refine or update the models that were devised to explain the existence of 51 Peg-like planets.

We can divide the models for the existence of planets with short orbital periods into three broad categories. The most favored model is that of planetary migration (e.g., Lin, Bodenheimer, & Richardson 1996). In this model a planet is formed by core accretion at a distance of the order of 5 AU or further (but see Bodenheimer, Hubickyj & Lissauer 2000 for a somewhat different approach), and then is pushed toward the parent star by interaction with the accretion disk. Alternative models are migration by interaction with other planets (e.g., Weidenschilling & Marzari 1996) or planetesimals (Murray et al. 1998). A completely different approach assumes planet formation by disk instability (e.g., Boss 1997a). Obviously, if the instability ends up as a planet far away from the parent star, one needs a migration mechanism to account for the close-in planets (Boss 1997b). In what follows we will try to comment on the implications of our findings on each of the three categories of models.

Two effects within the migration scenario can contribute to the paucity of massive planets with small orbits:

(I) Massive planets open a gap in the disc, and consequently slow their migration rate substantially (e.g., Ward 1997; Trilling et al. 1998; Nelson et al. 2000). We expect, therefore, to find the more massive planets at distances closer to their formation sites.

(II) Trilling et al. (1998) pointed out that when planets get too close to their parent stars they loose substantial fraction of their mass through Roche-lobe overflow. In the specific parameters presented by Trilling et al., planets above 3.4 M_J do not migrate significantly from their formation site. Most of the planets with initial masses below 3.4 M_J loose substantial fraction of their mass through Roche-lobe overflow. In fact, planets with initial masses below 3.36 M_J loose most of their mass, and are left with masses smaller than 0.4 $M_\odot$.

The two effects, discussed already by theoretical studies of the migration model, contribute to the paucity of very massive planets with small orbits. The second effect contributes to the mass-radius correlation for short distances, on the order of tenths of an AU, whereas the first effect dominates the correlation for larger distances. Actually, Trilling et al. (1998) already published a mass-period diagram with a series of models they ran (see their Figure 7), in which the effect we find here can be clearly seen.

However, the first effect can be canceled out if the planet mass depends on the disk mass. This is so because the size of the gap depends on the ratio between the planet mass and the disk mass (e.g., Trilling et al. 1998). Suppose, for example, that the planet mass scales with the disk mass. Then more massive planets could move inwards before they opened a gap as much as less massive planets do. Therefore, to account for the correlation we see in the data we have to assume that planets are formed with *masses that do not scale with the disk mass*. In other words, planets with different masses can be formed in disks with similar masses.

Interaction with other planet(s) was suggested mainly to explain the high eccentricities observed for some of the known extrasolar planets (e.g., Weidenschilling & Marzari 1996, Rasio & Ford 1996; Ford, Havlickova & Rasio 2001). A few models include an accompanying disk that absorbs the angular momentum necessary to enable the migration (e.g., Murray, Paskowitz & Holman 2001).

Suppose the interaction with the other, as yet undetected, planet is the dominant mechanism for the migration of the known planet. Such a scenario can account for the observed mass-period correlation if the mass of the undetected planet is independent of the mass of the known planet. In such a case, the ability of the unseen planet to push the known planet to smaller radii is limited only to small-mass planets, consistent with the mass-period correlation we see in the data. If, on the other hand, the mass *ratio* between the planets is similar in all planetary systems, the migration caused by the planet-planet interaction should not be limited to small-mass planets, contrary to our findings.

The same argument applies to migration driven by interaction with planetesimals. Murray et al. (1998) comment that "if the mass of the planetesimal disk interior to the planet is of order of the planet mass, the planet can migrate nearly to the surface of the star". In other words, the migration depends on the mass ratio between the planet and the planetesimal disk. Therefore, to account for the observed mass-period correlation we have to assume that the planet mass does not scale with the mass of the planetesimal disk.

Planet formation via disk instability (Boss 1997a; 1998a; 2000; 2001) could also account for the mass-period correlation, in principle, if we assume an in-situ formation for this model. We can speculate that the mass of the forming planet depends on the mass available in the disk at the vicinity of the instability. Suppose, for example, that the mass associated with the instability is some fraction of the mass within the radius of the instability center. This can lead to more massive planets forming at large distances, hence the effect we have detected. However, one still needs to establish by detailed numerical simulations that this model can work at small distances from the star. If, on the other hand, the disk instability can work only at large distances, and thus still requires a mechanism for migration, then dependence of the planet mass on the disk mass might make it difficult to account for the paucity we detected.

Two theoretical studies have considered the implication of binarity of a star on the formation of planets around one of its components. One report on numerical study (Boss 1998b) indicated that the presence of a stellar companion can induce a rapid instability even for disks that are stable otherwise. A somewhat more recent work (Nelson 2000) suggested an opposite effect, claiming that planets are unlikely to form in certain binary systems. Both works dealt only with a companion at a distance of 40–50 AU, and more comprehensive studies are needed to explore the implication of a companion on planet formation. In any case, both works indicate that the planets in binary systems might not have the same mass-period distribution, consistent with our findings.

To summarize, it seems as if almost all models for the existence of close-in giant planets can account for the mass-period correlation of the single-star planets, although the correlation seems a more natural outcome of the model that assumes migration driven by a disk-planet interaction. In any case, this correlation can put, in principle, some constraints on the different models. The number of planets known today is only marginally enough to characterize the details of the short-period–massive-planets deficit, apart from establishing its existence. Nevertheless, we already can conclude that for all models we need planet masses that do not scale with the mass of the disk/planetesimals/other planets. More data can illuminate the finer details of this phenomenon and help to better tune the theories for close-in giant planets.

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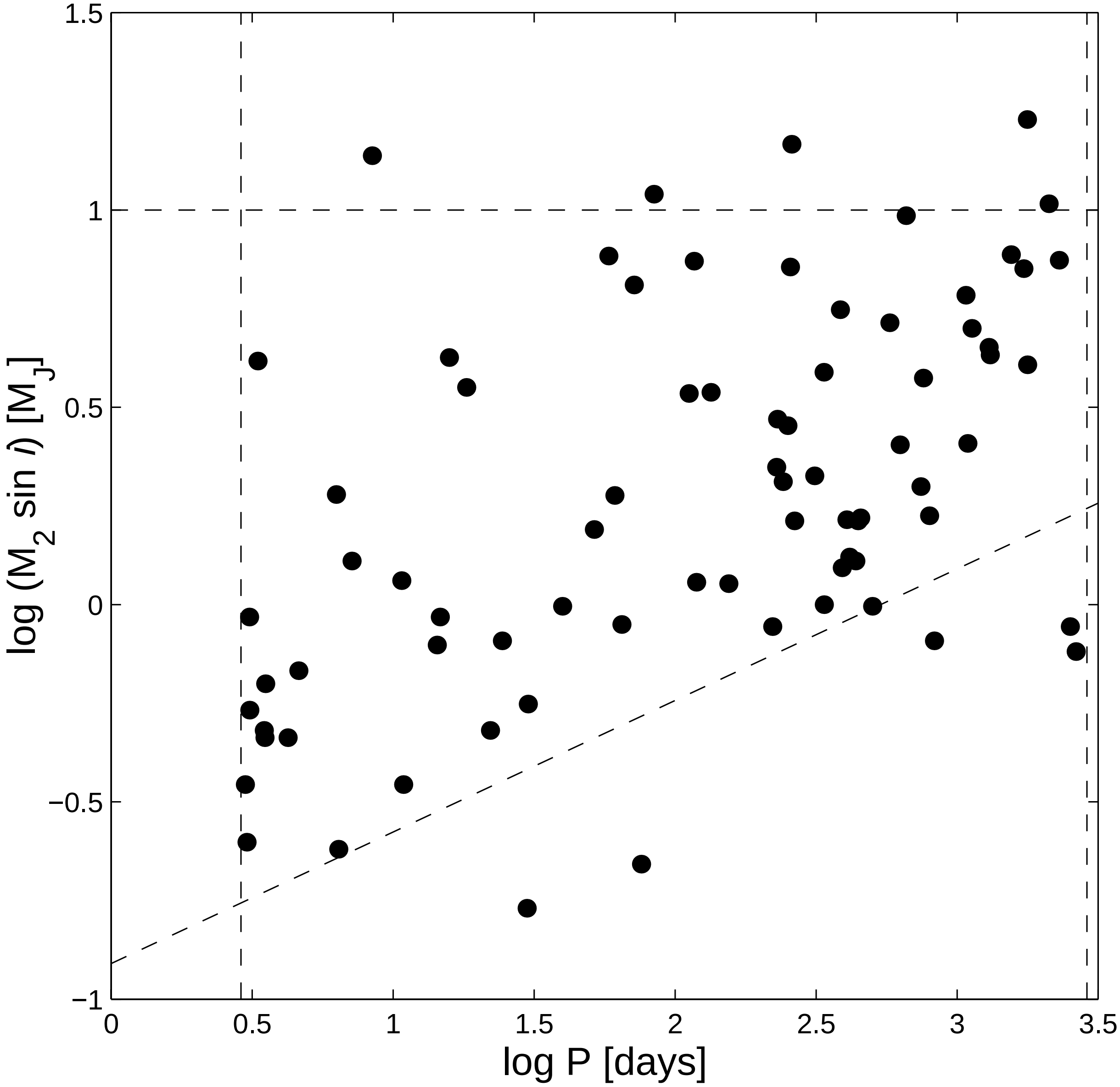

Fig. 1.— The minimum mass vs. the period of the extrasolar planets. The four dashed lines and the trapezoid they form are explained in the main text.

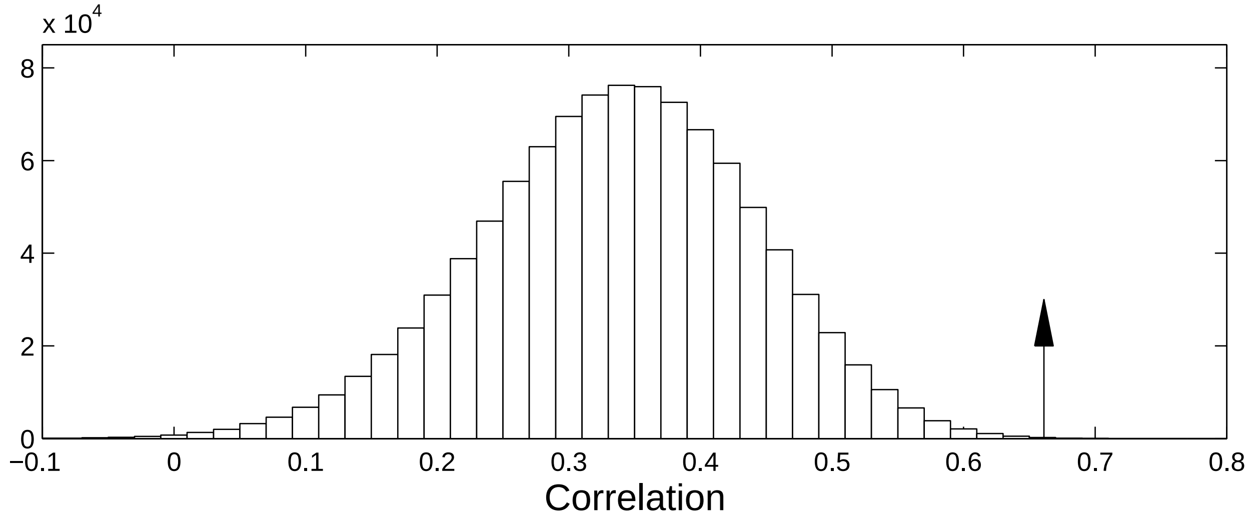

Fig. 2.— Histogram of the correlation coefficients calculated for random samples drawn out of a uniform distribution in log-mass and log-period.

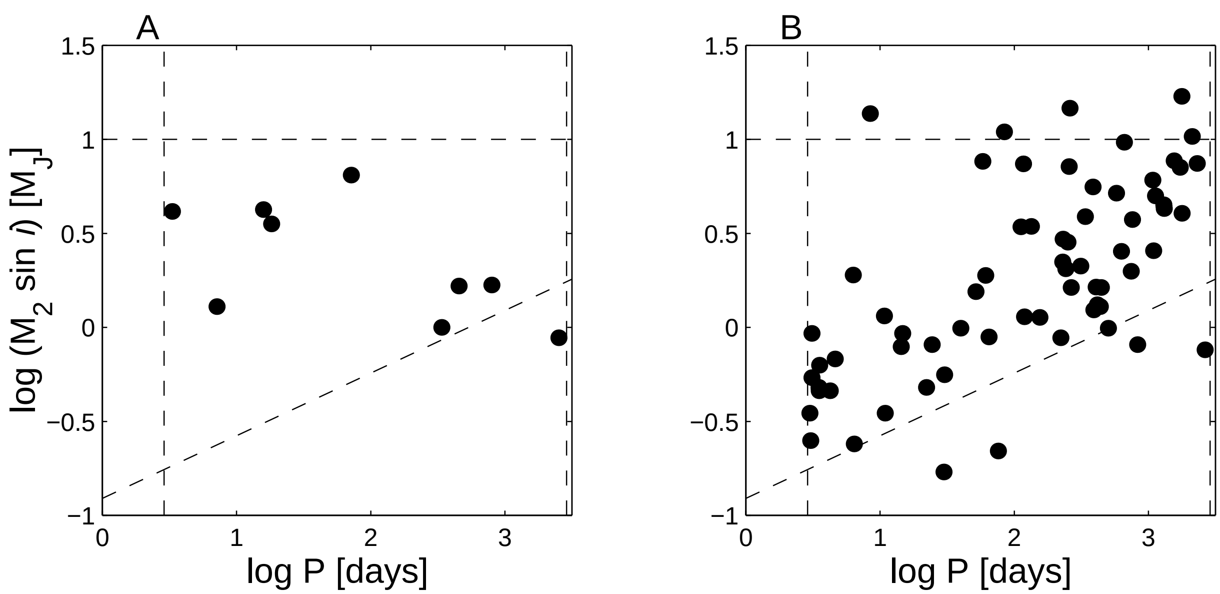

Fig. 3.— The minimum mass vs. the period of the extrasolar planets for the binary stars (A) and the non-binaries (B). The four dashed lines and the trapezoid they form are explained in the main text.

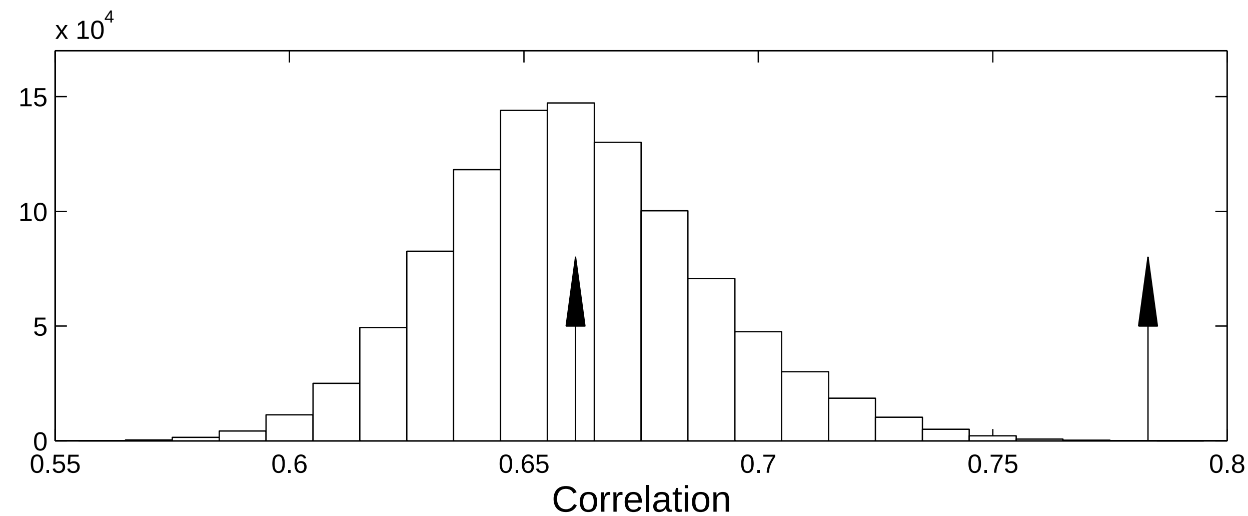

Fig. 4.— Histogram of the correlation coefficients calculated for 10^6 times of randomly removing 8 planets out of the original sample. The arrows indicate the values of the correlation before removing the 8 planets found in binary systems (left arrow) and after removing them (right arrow).